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# Solar greenhouse an option for renewable and sustainable farming

N.L. Panwar[a,*], S.C. Kaushik[a], Surendra Kothari[b]

[a] Centre for Energy Studies, Indian Institute of Technology, Hauz Khas, Delhi 110016, India
[b] Department of Renewable Energy Sources, College of Technology and Engineering, Maharana Pratap University of Agriculture and Technology, Udaipur (Rajasthan) 313001, India

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ABSTRACT

Greenhouses provide a suitable environment for the intensive production of various crops. They are designed to provide control as well as to maintain solar radiation, temperature, humidity and carbon dioxide levels in the aerial environment. $CO_2$ enrichment decreases the oxygen inhibition of photosynthesis and increases the net photosynthesis in plants. This is the basis for increased growth rates caused by $CO_2$ at low as well as at high light levels. Elevated $CO_2$ concentrations also increase the optimal temperature for growth. The maximum crop response depends on the level of the balanced environmental parameters. Off seasonal cultivation is quite possible in greenhouse and it improves economic conditions of farmers. This paper reviews the available worldwide thermal modeling for heating, cooling and ventilation technologies and experimental studies of agricultural greenhouses.



**Contents**



## 1. Introduction

The great impact of population increase as well as rapid economic growth has given us cause for concern about the future situation of the earth in recent years. Desertification as well as deforestation has been change the landscape in recent years. Irrigation areas are being damaged by salinization. The effect to increase arable lands cannot match with the speed of these deteriorating processes. Weather is also being changed gradually by urbanization. In the new millennium the challenges in the agricultural sector are quite different from those met in the previous decades. The enormous pressure to produce more food from less land with shrinking natural resources is a tough task for the farmers. This is call for special effort to manage the key input without eroding the ecological assets and sound knowledge base to sustain agricultural productivity and profitability [1].

The maximum crop response depends on the level of the balanced environmental parameters. The natural environment and input availability may not be optimum for a given crop. The environmental factors which effect plant growth includes air temperature, relative humidity, carbon dioxide concentration, soil temperature and moisture content to the soil. The micro-climate can be artificially controlled by means of plastic covering structure like greenhouse. The plastic covered greenhouse is the only mechanism, which transmits the useful wavelengths of light spectrum for photosynthetic activity. Further, it also reduces the air movement, which is of great importance for the plant growth and often used to control the spread of plant diseases [2].

Sun is the main sources of energy in the universe. As far as plant propagation is concern sunlight provides the primary energy for photosynthesis, the food chain and all human nutrition. The expansion of crop and flower production in various types of greenhouse

* Corresponding author. Tel.: +91 294 2471068; fax: +91 294 271056.
*E-mail address:* nlpanwar@rediffmail.com (N.L. Panwar).

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**Nomenclature**

| | |
|---|---|
| $C$ | $CO_2$ flux (kg/m$^2$ s) |
| $C_{pair}$ | specific heat of air |
| $E$ | water vapour flux (kg/m$^2$ s) |
| $H$ | sensible heat flux (W/m$^2$) |
| $L$ | far infra-red (FIR, long-wave) radiation flux (W/m$^2$) |
| $m_{air}$ | mass of air inside the greenhouse |
| $m_{cover}$ | mass of cover material |
| $N$ | near infra-red (NIR, part of solar) radiation flux (W/m$^2$) |
| $P$ | photosynthetically active radiation (PAR) flux (W/m$^2$) |
| $T_{air}$ | air temperature |
| $T_{cover}$ | cover temperature |
| $q_{in-cover}$ | heat to cover |
| $q_{out-cover}$ | heat out cover |
| $q_{sun-to-cover}$ | sun radiation absorbed by cover |
| $q_{conv-air-to-cover}$ | heat transfer by convection from air to cover |
| $q_{condens-air-to-cover}$ | heat transfer by condensation of water vapour in inside cover |
| $q_{wind}$ | heat transfer by convection from wind to cover |
| $q_{thermal\ radiation-cover}$ | net thermal radiation at cover |
| $q_{in-air}$ | heat to air |
| $q_{out-air}$ | heat out air |
| $q_{conv-soil-to-air}$ | heat transfer by convection from soil to air |
| $q_{evap-soil-to-air}$ | heat transfer by evaporation from soil to air |
| $q_{inf}$ | heat losses from infiltration |
| $q_{ventil}$ | heat losses from ventilation |
| $q_{condu-to-soil}$ | heat by conduction in soil |
| $q_{sun-to-soil}$ | sun radiation absorbed by soil |
| $q_{thermal\ radiation-soil}$ | net thermal radiation from soil |
| $\Lambda$ | leaf area index (leaf/floor ratio) |

*subscripts*

| | |
|---|---|
| $a$ | inside air |
| $b$ | lower (inside) cover of greenhouse |
| $c$ | thermal capacity of air at constant pressure (J/kg K) |
| $e$ | due to operation of equipment |
| $i$ | infiltration |
| $l$ | leaf, canopy |
| $o$ | outside (above) greenhouse |
| $t$ | upper (outside) cover of greenhouse |

during the recent years has enabled the growth of agricultural products through the entire year [3,4]. An agricultural greenhouse is consisting of frames of metallic or wooden structure covered with a transparent material which provide a suitable environment for the intensive production of various crops. A greenhouse is essentially an enclosed structure, which traps the short wavelength solar radiation and stores the long wavelength thermal radiation to create a favorable microclimate for higher productivity [5,6]. Open field agricultural farming has no control on the environmental parameters such as sunlight, air composition and temperature that influence the plant escalation. Hence, a large number of winter vegetables, flowers and other horticultural crops have to be transported from distant places [7]. Future greenhouse systems in moderate climates will have to be energy efficient. Greenhouses will have decreased transmission for long-wave- and increased transmission for short-wave-radiation compared with common shelters [8].

Computerised control is an intrinsic part of present day modern greenhouses. The functions of the climate computer can be summarised as follows: (i) it takes care of maintaining a protected environment despite fluctuations external weather (controller function); (ii) it acts as a programme memory, which can be operated by the grower as a tool to steer his cultivation [9]. Its control is moving towards model-based optimal systems [10], which results in the development of various kinds of dynamic models [11].

In the present paper attempt has been made to review the developments in greenhouse technology particularly for crop production including the thermal model developed by various researchers for cooling, heating and ventilation. Here we try to present a very brief summary of the earlier work on greenhouse structural analysis and crop production performance. This is intended only to provide the background to the reader on greenhouse technology as an option for renewable and sustainable development.

## 2. Thermal modeling of greenhouse

Guttormsen [12] investigated the effect of plastic tunnels on air temperature with a perforated area of 0.75, 1.3, 2.6, 3.9, 5.2, and 6.5% under varying weather conditions as defined by cloud cover observations. The diameter of opening was 10 cm. He calculated the effect on temperature for daytime maximum, nighttime minima; 24 h range average and daily sequence of temperature. Perforation resulted in marked reduction in the amount of heat and maximum day temperature. Though minimum nighttime temperature was lowered only as much as 1 °C. He concluded that the use of adequately ventilated tunnel together with an extended period of covering towards harvesting seemed to imply considerable advantage over conventional method of cultivation. The best method of determining the temperature within greenhouse was found by Hanan et al. [13]. It was pointed out that every user should record it at specific intervals of 24 h when temperature is recorded sensing element should be at plant height and not two or three feet above or below the crop.

Kindelam [14] developed a dynamic model of greenhouse, which is based solely on primary boundary conditions and including the heat storage capacity of the soil. In order to simulate the internal environment by the energy balance method, the system is divided into four elements soil, plant, internal air and covering modeling the heat and mass fluxes between these elements. The following results were obtained:

(i) The humidity during the night increases with increasing external temperature, with decreasing solar radiation and with decreasing amplitude of oscillation.
(ii) For an empty greenhouse the maximum temperature is very high and the relative humidity is low.
(iii) It is observed that with ventilation both the temperature and humidity decrease during the day, although during the night, the humidity increases because there is no ventilation and the temperature is lower.
(iv) Just before sunset and near sunrise an increase in relative humidity and evaporation rate increases with the ventilators still close, followed by a steep drop when the ventilators are opened.

When heating is used at night, the air temperature increases and the relative humidity decreases. This fact would be used to prevent the high humidity conditions occurring at night during warm weather.

Arinze et al. [15] developed a dynamic mathematical model for predicting temperatures and moisture levels in a solar assisted energy conserving circular type greenhouse. They investigated the active passive forms of thermal storage. Other energy conservation features incorporated into test greenhouse included arch shutter thermal insulation applied in between the double layered inflated

transpired plastic covers at night to reduce heat losses or heat gain. Later, they programmed the greenhouse thermal model on digital computer and comparisons of the greenhouse measured variables with model predictions showed a high degree of correlation. The extended thermal model can also predict adequately the greenhouse energy consumption, accuracy of the computer model prediction depend greatly on the time steps used. They faced a problem of convergence in the computer runs for time steps larger than 900 s and convergence for all runs and sufficient accuracy was obtained for time steps between 300 s and 600 s.

Tiwari [16] analysed winter greenhouse. Effect of various parameters viz. ventilation/infiltration, relative humidity, movable insulation etc. have been incorporated in the analysis and their effect on performance of greenhouse was studied. He reported that temperature rise of the plant and room air is increased up to about 3–5 °C by covering the system with movable insulation. The performance of the greenhouse is improved by concrete north wall. It reduces the heat losses during the night.

Tiwari and Dhiman [17] presented a design and mathematical model for a winter greenhouse at Leh, Jammu and Kashmir in India. In this part of the country, the ambient air temperature in winter season dips down to −30 °C and goes up to a maximum of about 25 °C in summer. Growing vegetable is difficult in this climate. Since the transportation of vegetable and other articles to this place is a problem greenhouses are essential for the growth of vegetables. Here greenhouses are possible because solar insulations are available for almost 11 months of the year. Numerical calculations show that a glass wall on the south side and an insulated wall and roof on the north side give good results.

Seginer et al. [18] made on attempt to calibrate in situ a greenhouse model of moderate complexity, which can be used as a tool in simulation and optimization studies, related to energy conservation in green house. For that purpose, they developed a six element linearized steady state model of a double cover, dry greenhouse without a crop and used to evaluate four convective heat transfer coefficients, two radiation transmissivities, one radiative shape factor and a heat flux. They covered a small (20 m$^2$ floor area) green house frame consecutively with four different polyethylene covers. There were the four combinations of regular and high emissivity polyethylene sheets on the one hand, and single and double layer (inflated) covers on the other. Various heat fluxes and temperatures were measured. Further, they analysed the data obtained for the four covers simultaneously assuming the radiative and convective coefficients independent of each other and the same value of local coefficients for all covers. In particular, the inside and outside convective transfer coefficients were assumed to be same for all covers. They concluded that a double layer cover is generally more effective than a single layer cover in maintaining high inside temperature and the sheets with higher absorptivity are more effective than the regular ones in maintaining high inside temperature. The results suggested that the basic assumptions of the model (linearity independence of coefficients) are valid for engineering purposes.

Critten [19] developed an analytic expression for the light transmission viewed from any point across an infinitely long single span greenhouse. For first order reflections they assumed that reflected energy per unit reflecting surface area is independent of angle of incidence, produces a satisfactory prediction of detailed light transmission in single span greenhouse under diffuse over cast radiance conditions. This approximation appears to be generally valid and can be used for prediction of light transmission in any number of spans, double or single clad with or without walls and under general radiance conditions. For second order, reflected energy per unit beam cross section assumed constant with incidence angle. This being a less accurate assumption than the previous one, the fraction loss at normal incidence appears to provide an acceptable value of *K*.

Zanan [20] states that humidity is induced by plants transpiration and by evaporation from irrigation water. The control of relative humidity inside a greenhouse is very important as excess can be origin of virus diseases to plants. The humidity will further more condense over the cold structures of the greenhouse. The most important one is constituted by the film covering. Here the condensation plays two negative effects:

(i) Small droplets on the surface causing a drastic reduction in the light transmission due to deflection of rays by the spherical shape of droplets.
(ii) Coalescence of small droplets in larger one causing a rainfall down to the crops, with subsequence damage because of shocks and burns on leaves and flowers.

Always control of humidity and temperature to be accomplished by means of proper ventilation of greenhouse.

Silva et al. [21] offered a model which yielded the net thermal radiation at the ground of a single span greenhouse fitted with thermal screens, in terms of the outside radiative environment, the properties of the cladding and screening surfaces and the temperatures of ground, screen and covering. Radiation was assumed to be diffusively emitted, transmitted and reflected, both by the cladding and the screening surfaces. The importance of geometry and temperature of screening surface and of the radiometric properties of the screen in determining the radiative, environment inside were indicated by them. On the basis of this model, together with the outside radiation fluxes, temperature of the ground, screen and cover and data on the thermal radiation inside the greenhouse can be determined, both in clear and over cast night sky conditions. These results were found to be in fairly good agreement with the measured net thermal radiation at ground level inside the greenhouse.

Jolliet [22] presented model to predict humidity and transpiration directly as a function of the outside climate, with the particular objectives of developing optimal control strategies for humidity in greenhouse. The developed model includes the processes of transpiration, condensation, ventilation and humidification or dehumidification. The model allows the inside vapour pressure to be directly calculated as a function of the outside condition and the greenhouse characteristics. It includes a linear relationship for transpiration, which is good approximation of a more detailed model. Condensation on the cladding is first calculated for the inside greenhouse air at saturation and then corrected by a factor to account cladding temperature. Because of its simplicity this model also explicitly determined the water and energy to be added to or extracted from the greenhouse air, in order to achieve given humidity or transpiration set points.

Vollebregt [23] was developed a calculation method to analyse the heat flows of a greenhouse wall by combining steady-state heat balance calculations and a simulation model of the airflow near the wall and the adjacent heating system. Heat exchanges by radiation between the wall, heating pipes, interior and exterior of the greenhouse were taken into account by deriving radiation absorption factors from the geometry and optical properties of the surfaces. Convective heat transfer coefficients at the wall were determined with an airflow simulation program. The accuracy of the simulation modeling technique used was validated by comparing simulation results of detailed problems with data from literature. The local convective heat transfer coefficient at the inner side of the wall of a standard Venlo-type greenhouse appears to vary with height between 4 and 9 W m$^{-2}$ K$^{-1}$ and is on average 6.7 W m$^{-2}$ K$^{-1}$ under Dutch design conditions. The analysis showed that about 20% of the heat released by the heating pipes near the wall is radiated towards and absorbed by the wall and about 30% of the total heat loss through the wall is compensated by radiative exchange from

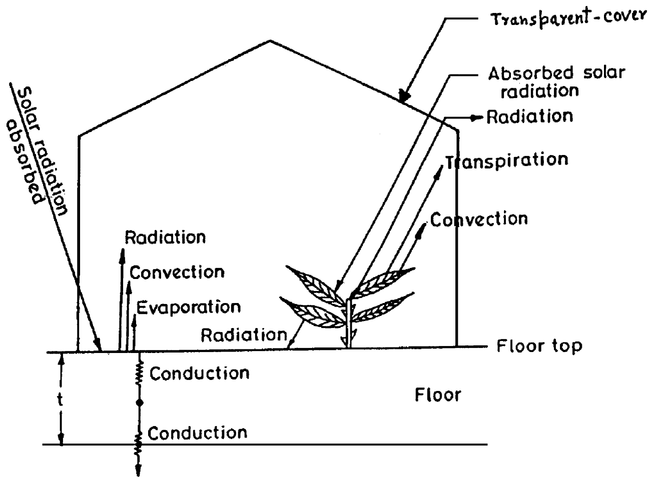



**Fig. 1.** Energy transfer mechanism in a greenhouse.

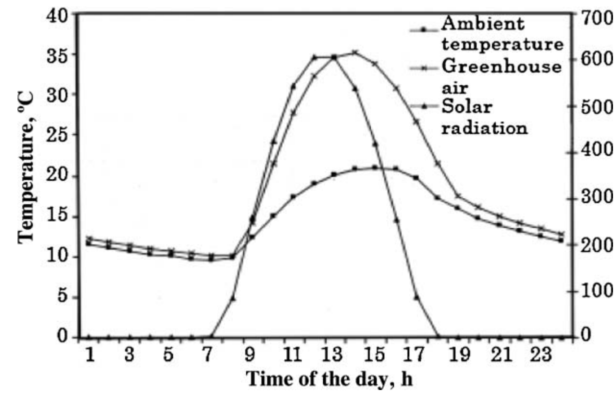



**Fig. 2.** Hourly variation of greenhouse air temperature.

the greenhouse interior. Predictions of the vertical temperature distribution of a greenhouse wall in practice were within 1–2 K.

de la Plaza et al. [24] developed a model to substrate heating system for greenhouse crops. The object is to predict the temperature of the substrate and to estimate the energy consumption. The model was validated experimentally in a localized heating installation of the substrate by using an electric cable and applied to a crop of gerbera (*Gerbera jamesonii* H. Bolus ex Hook) in a greenhouse. Different configurations in the design and operating methods for the electric substrate heating were examined over a period of two years.

Rachmat and Horibe [25] conducted study on application of solar energy in a Fiber Reinforced Plastic (FRP) house designed for a brown rice drying system with the objectives:

(1) The temperature variation inside the house.
(2) The effect of solar radiation and airflow rate on the temperature difference between the air inside and outside the FRP (house) and
(3) The heat collection efficiency of an FRP house.

They reported that for global solar radiation in the range of 100–800 W/m$^2$, the temperature rise shown an exponential relationship with global solar radiation and the values of temperature raise are higher when using a collector (5–16 °C) than when not using one (4–11 °C). The installation of FRP inside house increase heat collection efficiency of the house around 27–23%.

The analytical thermal model to predict microclimatic condition inside the greenhouse was developed by Kothari and Panwar [26] and validated with Udaipur climatic conditions. Different heat transfer mechanism in greenhouse is illustrated in Fig. 1. It is clear from Fig. 2 that the temperature rise in greenhouse air is up to 14 °C over ambient temperature during sunshine hours. The maximum temperature reaches in greenhouse 34.11 °C at 13 h. The minimum temperature inside the greenhouse is 10.05 °C at 7 h. Similarly, maximum and minimum floor temperatures inside the greenhouse are 39.23 °C and 10.1 °C at 14 h and 8 h, respectively. Maximum and minimum crop temperatures are 35.43 °C and 9.91 °C at 14 h and 7 h, respectively.

The greenhouse is considered to consist of five isothermal elements (layers): the crop canopy, inside air, inner cover, outer cover and outside air. The greenhouse is assumed to have an insulating floor and no heat capacity. The greenhouse function consists of six simultaneous steady state energy conservation equations [27], as follows:

1. Energy balance of canopy

$$(P_{al} - P_{lb}) + (N_{al} - N_{lb}) + (L_{al} - L_{la}) + H_{la} - \Lambda E_{la} = 0$$

2. Sensible heat balance of inside air

$$H_{al} + H_e - H_{ab} - H_i = 0$$

3. Water vapour balance of inside air

$$E_{la} + E_e - E_{ab} - E_i = 0$$

4. $CO_2$ balance of inside air

$$C_c - C_{al} - C_i = 0$$

5. Energy balance of inner cover

$$(P_{tb} - P_{bt} + P_{lb} - P_{bl}) + (N_{tb} - N_{bt} + N_{lb} - N_{ba}) + (L_{tb} - L_{bt} + L_{lb} - L_{ba}) + (H_{ab} - H_{bt}) + E_{ab} = 0$$

6. Energy balance of outer cover

$$(P_{ot} - P_{to} + P_{bt} - P_{tb}) + (N_{ot} - N_{to} + N_{bt} - N_{tb}) + (L_{ot} - L_{to} + L_{bt} - L_{tb}) + (H_{bt} - H_{to}) = 0$$

Humidity is one of the key factors in greenhouse climate. It usually tends to be high due to crop transpiration. The transpiration of the crop depends on solar radiation, $CO_2$ concentration, temperature of the greenhouse air and relative humidity in the greenhouse. Crops exposed to high humidity levels have a higher risk of developing fungal diseases and physiological disorders [28]. Three dehumidifying methods, being condensation on a cold surface, forced ventilation using a heat exchanger, and an absorbing hygroscopic dehumidifier, were compared with ventilation as the conventional way to dehumidify a greenhouse by Campen et al. [29]. It was found that dehumidification with a cold surface by applying a heat pump is not cost-effective when the heat pump is not used for heating as well. For heating with a heat pump, a heat source has to be available, for example an aquifer. This will increase the cost of the total system. Dehumidification with a hygroscopic material has the advantage that latent heat is directly transformed into sensible heat. However, the heat needed for regeneration of the material, the environmental risks and the complexity of the system make it less suitable for a practical application. The most promising method for dehumidification is forced ventilation with heat exchange. A low cost and efficient system has to be developed

in order to make it a success. In greenhouses with a higher insulation the system saves even more energy than in the normal single glass greenhouse.

Heating applications in the greenhouses have an important effect on the yield as well as on the quality and the cultivation time of the products. Because of the relatively high cost and uncertain availability of fossil fuels, considerable attention has been given to new and renewable energy sources as an alternative means of heating greenhouses. Solar energy is an attractive substitute for conventional fuels for passive and active heating of greenhouses. Solar thermal energy can be stored as sensible heat, latent heat, heat of reaction or combination of these.

An experiment was conducted by Bascetincelik et al. [30] to stored solar energy using the paraffin with the latent heat technique for heating the plastic greenhouse of 180 $m^2$. Energy and exergy analyses were applied for evaluation of the system efficiency. An average value of the rates of heat and thermal exergy stored into the HSU was 1740 W and 60 W for the charging periods, respectively. It was determined that the average values of the net energy and exergy efficiencies of the system were 41.9% and 3.3%, respectively.

## 3. Structural analysis

Cooper and Fuller [2] developed a method to assist in the design of low energy protected cropping structure to be used in the hot, arid inland climate of Australia. They considered greenhouse to be composed of a number of separate but interactive components. These are the cover, floor, growing medium, air space and crop. They used tomato crop model, which responds to photosynthetically active radiation, leaf temperature and $CO_2$ level. The design criteria were that the greenhouse should use only a small amount of conventional energy for heating when necessary and that they must operate all times in an essentially sealed condition for continuous $CO_2$ enrichment. To satisfy the first criterion, solar air heaters, a rocked pile thermal store and a moveable thermal screen were incorporated in the simulation model. The second condition was met by simulating the performance of a total enthalpy wheel and evaporative cooler, which dehumidifies and cool without ambient venting of the greenhouse. They stimulated performance of a number of different greenhouse types in winter and summer and analysed the stimulated crop yields, energy flows and temperatures indicating that the model was simulating the expected trends in greenhouses.

Ventilation study of greenhouse was conducted by Feuilloley et al. [31] and it is very important matter for the Mediterranean areas. At the beginning of April, the temperature rises at such a rate that it is impossible to obtain a crop without good ventilation system. Generally grower has to stop any work in greenhouse with bad effect on economy. The proposed site should not be located in the vicinity of an industry as its down wind side because of possible pollution effect on green house crop. The location should be fairly shadow free, there should be sufficient room for the expansion of the facility in future [32].

Briassoulis et al. [33] reported that covering materials of greenhouses in use today in Europe are classified and analysed with respect to their use. Glass still appears to be one of the most widely used materials in Northern Europe. However, the development of new plastic materials has led to a significant increase in the overall share of plastic covered greenhouses in Europe and their complete domination in Southern Europe. The mechanical properties of greenhouse coverings are very important in relation to their mechanical behaviour under various loading conditions and to the overall structural behaviour of the greenhouse. The ultimate design of a greenhouse has to represent a balance between the overall structural designs, the mechanical and physical properties of the cladding materials and the specific agronomic requirements of the crop. Installation of the covering materials to the greenhouse structure plays an important role in the overall mechanical performance of the covering. Another important factor affecting the mechanical behaviour of the covering materials of greenhouses is the environment. In general, the mechanical properties of the covering materials of greenhouses (combined with the physical properties) are found to be critical in determining the relevant requirements concerning the structural design and construction details of a greenhouse.

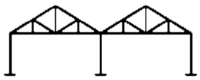
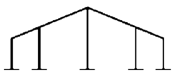
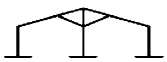
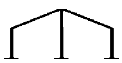
Geoda et al. [34] conducted an experimental model greenhouse for investigation of solar radiation transmission and aging of cladding materials in general, and of anti-drop materials in particular, was designed and constructed. The experimental greenhouse is supported by a turntable and can be turned to compensate for changes in surface azimuth angle of the sunrays, allowing nominal solar radiation transmissivity measurements at any season and any time of day. The experimental greenhouse which comprises eight identical sections was covered by four types of polycarbonate structured sheets. The sheets were tested for their transmissivity in a dry state and in a wet state (under condensation). In both states, the solar radiation transmissivity of the sheets under an accumulation of dust and dirt as a function of time was studied. The deterioration of surface-active additives in anti-drop sheets was studied. It is estimated that the experimental greenhouse accelerates the aging of surface-active additives in anti-drop cladding materials by a factor of three.

Elsner et al. [35] reported that, the factors influencing the greenhouse design such as the climate, the local building regulations the indoor climate requirements and the necessary functional characteristics. The variations with respect to these factors observed throughout most of the European Union countries are described in detail and their influence to the greenhouse design is critically investigated.

Kendirli [6] studies four type most economic greenhouse structural analysis in Turkey it was reported that about 85% of greenhouses were placed in the east–west direction, 15% in the north–south direction. The dimension and material used in studied greenhouse is presented in Table 1. Placement of greenhouse in the east–west direction improves the efficiency of solar energy utilization. Due to improper constructions of the facilities, problems about greenhouse climate especially about greenhouse ventilation have arisen. Heating in 80% of the cut-flower producer greenhouses was performed by stoves, 90% of the greenhouses use natural ventilation.

Energy conservation in five shapes of the greenhouse (see Fig. 3) was estimated by Singh and Tiwari [36]. The theoretical available solar energy at the outer surface and inside the greenhouse is illustrated in Fig. 4. Since shape 2 has highest receiving area, hence available solar energy at the surface and inside the greenhouse is higher in shape 2. To maintain 25 °C temperature, total energy required, solar energy available and additional energy required are presented in Table 2. The table indicates that the total energy requirement to keep the plants warm is lowest in shape 5. It may be due to the minimum losses from the greenhouse to outside atmosphere in this shape. Table 2 reveals that the additional energy requirement is lowest in the case of shape 2 (standard peak uneven span shape). The reason for lowest addition energy requirement is due to the maximum availability of solar energy through solar radiation provided by its larger receiving area and lower overall heat loss. The additional energy is required due to non-availability of solar radiation during the off-sunshine hours and low intensity periods and heat loss from the greenhouse. The amount of additional fuel energy depends on the type of the fuel and it burning efficiency. The criteria for choice of the fuel are the availability of fuel and socioeconomic conditions of user.

**Table 1**
Structural characteristics of selected greenhouses.

| Greenhouse type | Dimensional characteristics of greenhouse (all dimensions are in meter) | | | | | Material characteristics (standard structural iron) |
|---|---|---|---|---|---|---|
| | Width | Length | Side height | Ridge height | Truss width | |
|  | 18.00 | 48.00 | 3.15 | 4.20 | 4.00 | Steel frame with $L_{60.60.6}$ |
|  | 11.00 | 45.00 | 2.20 | 4.00 | 3.00 | Steel frame with $L_{60.60.6}$ |
|  | 5.00 | 48.00 | 2.10 | 2.85 | 3.00 | Steel frame with $L_{60.60.6}$ |
|  | 8.00 | 45.00 | 2.00 | 3.50 | 3.00 | Steel frame with $L_{60.60.6}$ |

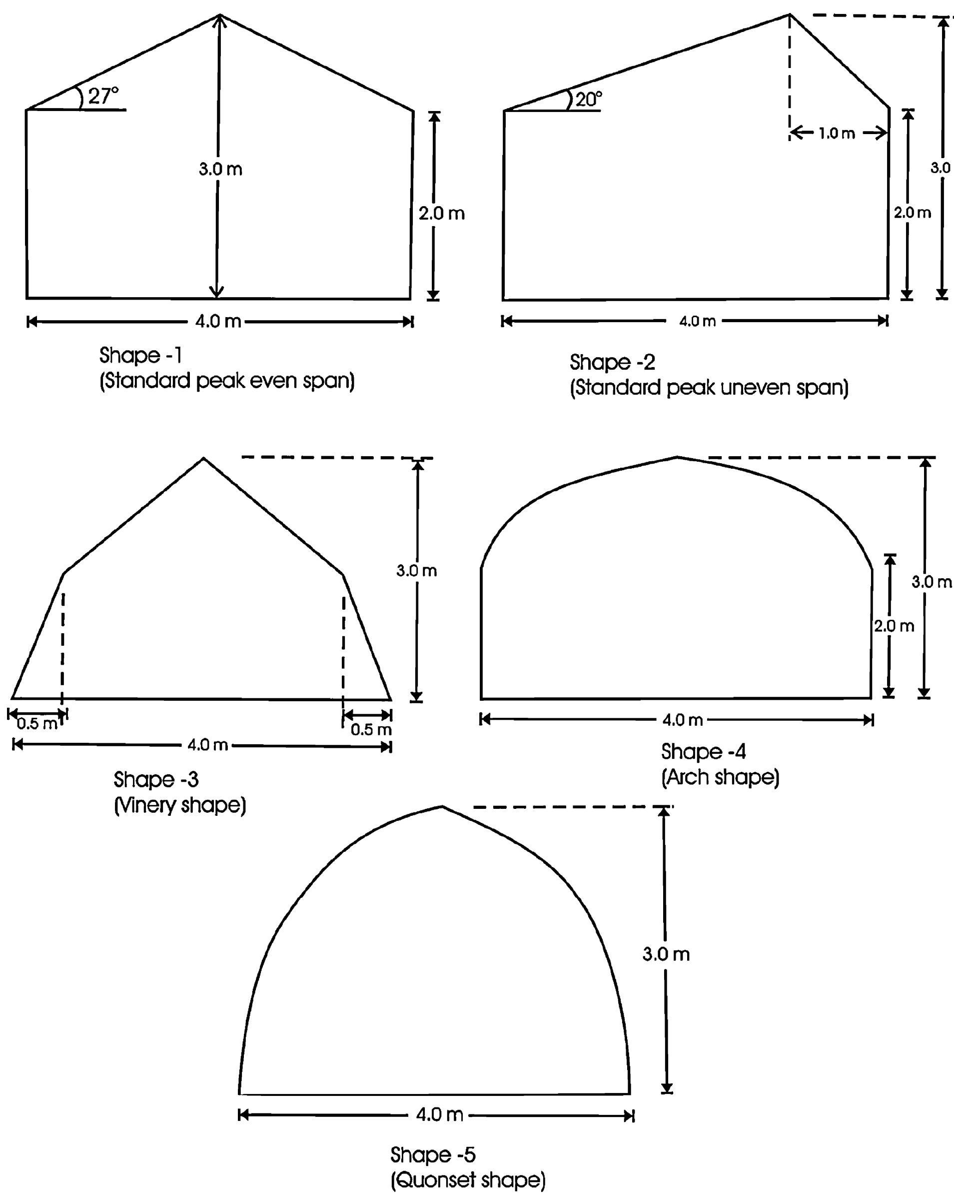



**Fig. 3.** Different shapes of greenhouse structures.

**Table 2**
Available and additional energy requirement at 25 °C.

| Shape | Total energy requirement (MJ) | Solar energy available (MJ) | Additional energy requirement (MJ) |
|---|---|---|---|
| Shape-1 | 223 | 109 | 114 |
| Shape-2 | 226 | 128 | 98 |
| Shape-3 | 213 | 102 | 111 |
| Shape-4 | 226 | 103 | 123 |
| Shape-5 | 198 | 94 | 104 |

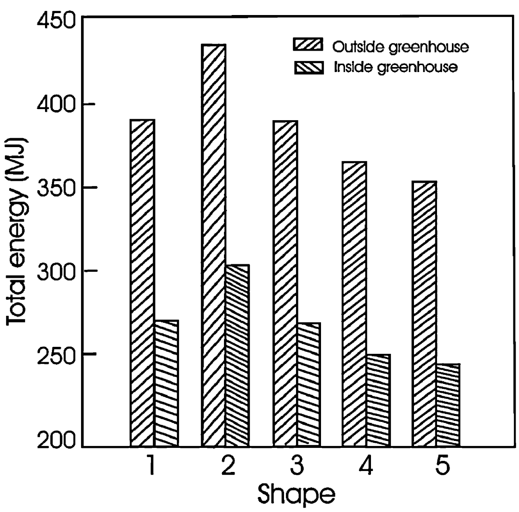



**Fig. 4.** Total energy vs. shape of greenhouse.

A simple dynamic greenhouse climate model was developed by considering the dynamics of external weather and crop parameters to predict greenhouse air temperature, water vapour pressure and canopy temperature by Kumar et al. [37]. The crucial parameters used in the model were obtained using Generic Algorithm optimization technique. The maximum temperature difference of 2 °C in the Sawtooth greenhouse and 4 °C in the Quonset greenhouse as against ambient condition was observed during winter season. In summer season, the maximum differences in temperatures in the Sawtooth and Quonset greenhouses were 4 °C and 6 °C, respectively. Consistent performance of the greenhouse climate model was observed for both the seasons at the validation stage with minimum RMSE values. Sensitivity analysis of the model parameters indicated that width of side ventilation, angle of roof vent and leaf area index influenced the model performance in predicting temperature. The greenhouse used to validate the model is illustrated in Fig. 5.

More solar radiations were trapped by greenhouse during the summer, it elevated the inside temperature and humidity. Therefore to maintain as well as to control the inside environment cooling is required. Morris [38] reported the greenhouse cooling potential by evaporative cooling through a simple equation. Landsberg et al. [39] presented a detailed treatment of the greenhouse evaporative cooling system. It has been observed by various authors [40,41] that the temperature can be lowered by 6–8 °C with evaporative cooling in greenhouses.

Jain and Tiwari [2] developed a mathematical model for experimental validation of the thermal behaviour in the greenhouse after evaporative cooling. Extensive experiments have been performed for an even span greenhouse of effective floor area of 24 $m^2$ and having a brick north wall (see Fig. 6). Greenhouse was divided in two temperature i.e. zone-I and zone-II as shown in Fig. 7. The temperature in the greenhouse increases along the length of the greenhouse due to receiving solar incident radiation. The predicted average temperature in zone-I and zone-II shows fair agreement with experimental values. The optimum parameters of the cooling system are: (a) length of green house as 6 m, (b) mass flow rate as 0.6 kg/s and (c) height of cooling pad as 1.75 m (with width of 3 m) for the given size and shape of greenhouse and climatic condition.

The utilization of greenhouses in Portugal, have to deal with some specific climate problems like frost, during winter and overheating in summer days. To overcome these problems thermal model was developed by Tavares et al. [42] to predicting the


**Fig. 5.** Greenhouses in the Field Water Management Laboratory, IIT Kharagpur.

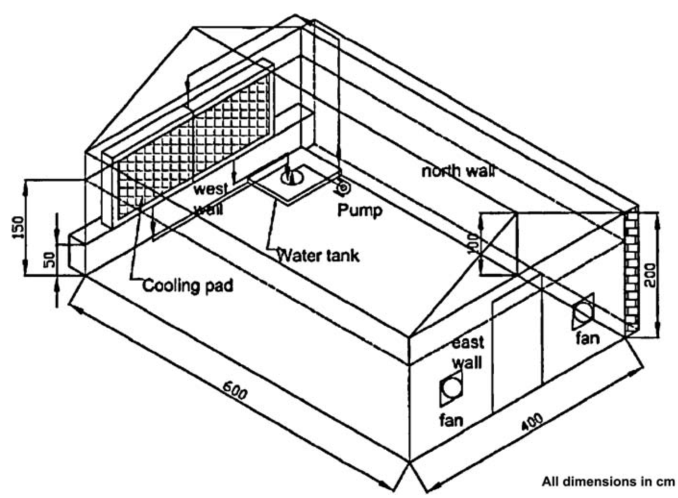



**Fig. 6.** Isometric view of greenhouse showing cooling pad with fan and water trickling arrangement and north wall.

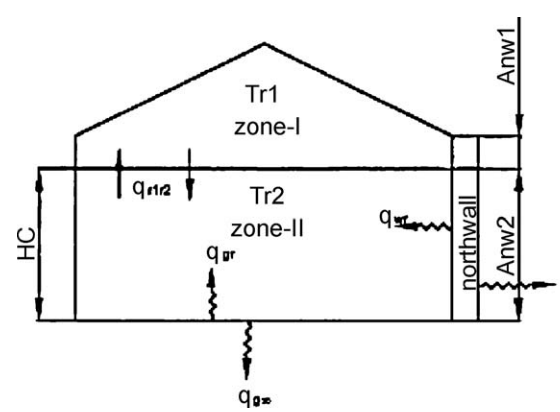



**Fig. 7.** Cross-sectional view of greenhouse showing zone-I and zone-II.

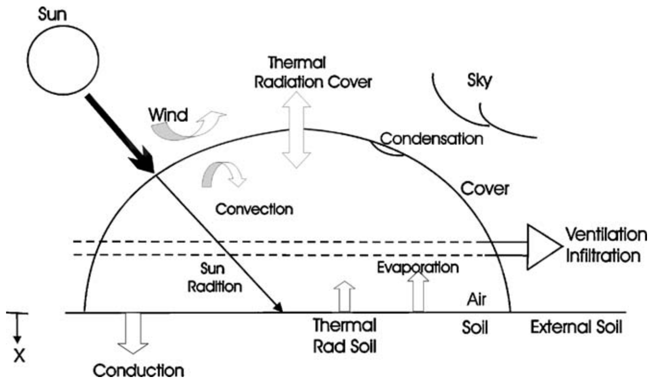



**Fig. 8.** Greenhouse heat and mass transfer fluxes.

thermal behaviour of a greenhouse under specific exterior conditions. The model was based on the solution of the one-dimensional heat balance equations in the greenhouse, and the results obtained are compared with experimental values measured in the 150 $m^2$ plastic covered greenhouse. The model considers a greenhouse divided into two control volumes, the covering material and the air inside, and a semi-infinite space, the soil beneath the greenhouse (see Fig. 8).

Heat balance equation in account of different heat flux used in model is as follows:

Heat balance equation for the cover material

$$m_{cover}C_{p\ \ cover}\frac{dT_{cover}}{dt} = q_{in\_cover} - q_{out\_cover}$$

where

$$q_{in\_cover} = q_{sun\_to\_cover} + q_{cone\_air\_to\_cover} + q_{out\_cover}$$

and

$$q_{out\_cover} = q_{wind} + q_{thermal\ \ radiation\_cover}$$

Heat balance equation for the air inside the greenhouse

$$m_{air}C_{p\ \ air}\frac{dT_{air}}{dt} = q_{in\_air} - q_{out\_air}$$

where

$$q_{in\_air} = q_{cover\_soil\_to\_air} + q_{evap\_soil\_to\_air}$$

and

$$q_{out\_air} = q_{conv\_air\_to\_cover} + q_{condens\_air\_to\_over} - q_{\inf} + q_{ventil}$$

One dimensional heat diffusion equation for semi infinite soil

$$\rho C_{p\ \ soil}\frac{\delta T_{soil}}{\delta t} = \alpha_{soil}\frac{\partial^2 T_{soil}}{\partial x^2}$$

with the following boundary conditions:

(a) at the soil surface a prescribed heat flux resulting from the surface energy balance:

$$q_{condu\_to\_soil} = q_{sun\_to\_soil} - (q_{conv\_soil\_to\_air} + q_{evap\_soil\_to\_air} + q_{thermal\ \ radiation\_soil})$$

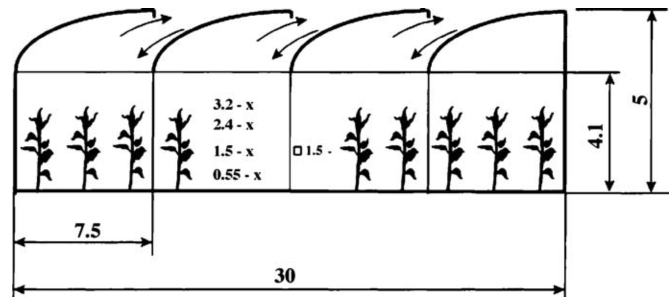



**Fig. 9.** A schematic view of the experimental greenhouse at Israel.

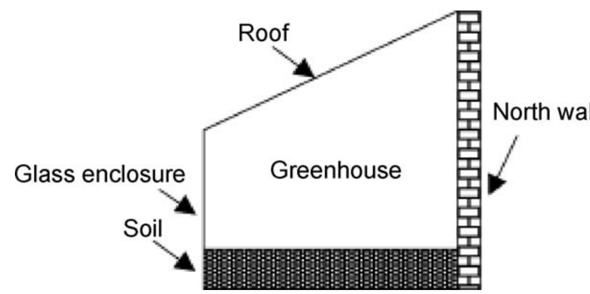



**Fig. 10.** Schematic of a lean-to type passive solar.

(b) at a certain prescribed depth an imposed temperature equal to a seasonal average ambient temperature

A model was developed by Teitel and Tanny [43] which describes the variation of temperature difference and humidity ratio difference in a naturally ventilated greenhouse, soon after the roof windows were opened. The model provides a supplementary tool in identifying greenhouse ventilation parameters. The model was validated with a four-span greenhouse with a floor area of about 960 $m^2$ and with gutters oriented north–south, as shown schematically in Fig. 9. The greenhouse was located in the south of Israel (31.28°N, 34.38°W, 75 m a.m.s.l.) and pepper trailed to a height of about 2.8 m was grown in it. The results show that the effects of the ventilation (i.e. the reductions in the temperature and humidity ratio within the greenhouse) increase with the height of the window opening and the wind speed, and decrease with the solar radiation level. Under the operating conditions, steady-state temperature and humidity ratio were reached at about $t$ = 3–4 (2300–3070 s). The non dimensional steady-state temperature and humidity ratio differences were always lower than 0.35 and 0.7, respectively, of their initial values. The window opening height may have a significant effect on the psychrometric process which the air within the greenhouse undergoes.

Numerical and experimental analysis of heat and moisture content transfer in a lean-to greenhouse was carried out by Chen et al. [44]. A lean-to passive solar greenhouse with a south inclining roof under investigation is shown schematically in Fig. 10. The roof and wall except the north wall consists of plate glass. A 60 cm wide massive wall is built at the north side of the greenhouse, which has two functions, one as a solar absorber, the other as a heat storage and insulator. Plant is neglected in the greenhouse, so the ground of greenhouse can be nearly taken as bare soil. From the developed model it was concluded that the temperature of the air, the soil and the wall in greenhouse is mainly influenced by solar irradiation. With increase in depth, the periodic variation range of the soil temperature and the moisture content in soil decreases, and the appearance of the peak temperature of soil postpones. During night, the moisture content in the upside of soil bed increases. Heat absorption, storage and insulation are the main factors in

**Fig. 11.** Naturally ventilated greenhouse.

greenhouse. So, the results should be taken into account for a better design and run of a greenhouse.

Dhakate [45] studied microclimatic conditions of naturally ventilated greenhouse conditions having 560 m$^2$ floor area (see Fig. 11) corresponding to open field conditions. The temperature difference inside the greenhouse was recorded as 10.3 °C and 9.0 °C more in the month of December and May respectively. Similarly the relative humidity was also high inside the greenhouse.

## 4. Effect of $CO_2$ enrichment

It is almost 200 years since the positive effects of $CO_2$ enrichment on plant growth were first observed. From about 1900 to the early 1930s, extensive $CO_2$ research was carried out in different European countries [46–48] and in the USA [49].

$CO_2$ enrichment decreases the oxygen inhibition of photosynthesis and increases the net photosynthesis in plants. This is the basis for increased growth rates caused by $CO_2$ at low as well as at high light levels. Elevated $CO_2$ concentrations also increase the optimal temperature for growth. Pot plants, cut flowers, vegetables and forest plants show very positive effects from $CO_2$ enrichment by increased dry weight, plant height, number of leaves and lateral branching. Plant quality expressed by growth habit and number of flowers is often enhanced by $CO_2$ enrichment. The rooting of cuttings is often stimulated by high $CO_2$ levels. The optimal $CO_2$ concentration for growth and yield seems to lie between 700 and 900 $\mu l\, l^{-1}$, and this $CO_2$ level is generally recommended in greenhouses. $CO_2$ concentrations higher than 1000 $\mu l\, l^{-1}$ might cause growth reductions and leaf injuries, and certainly do increase the loss of $CO_2$ due to leakage from the greenhouse [50].

Raising daytime temperature for crop fertilized with $CO_2$ has been generally beneficial. While raising the nighttime temperature has not also recommended an increase as much as 10 °F (6 °C) temperature for roses [51]. Ioslovich et al. [52] reported that greenhouse $CO_2$ enrichment, in warm climate is restricted by the need to ventilate, leading some growers to intermittent where enrichment and ventilation alternate several time an hour. This strategy relies on the heat and $CO_2$ capacity of the system, characterized by a heating time constant of the order of 10 min, during which weather; the period ventilation may be suspended. It was shown that, for slowly changing weather, the optimal $CO_2$ enrichment is basically not intermittent, but rather quasi steady state. As the disturbance frequency increase, the quasi steady state solution becomes less and less optimal. Udaikumar [53] reported where light intermission and duration are non limiting to achieve the high growth rate $CO_2$ fertilization has profound effect on increasing growth rate and relating the process of senescence. Short term $CO_2$ enrichment was shown to increases photosynthetic rate by providing more substrate for photosynthesis and decrease photorespiration. Carbon dioxide is a potent inhibitor of ethylene action and thus reduces the rate of senescence and improves quality of flowers and foliage plants.

**Table 3**
Thermo-physical properties of the rock bed and air.

| | |
|---|---|
| Equivalent diameter | 30 mm |
| Density | 1430 kg/m$^3$ (measured) |
| Porosity | 49% (measured) |
| Specific heat | 0.8 kJ/kg K (assumed) |
| Thermal conductivity | 2.9 W/m K |
| Air mass flow rate | 0.366 kg/s |
| Specific heat of air | 1012 J/kg K |

## 5. Cooling and ventilation

Natural ventilation is the direct result of pressure differences created and maintained by wind or temperature gradients. It requires less energy and equipment and is the cheapest method of cooling a greenhouse. It depends heavily on evapo-transpirational cooling provided by the crop [54]. Teitel et al. [55] investigated the airflow patterns and air temperature distributions in a naturally ventilated greenhouse with vertical roof openings using computational fluid dynamics technique. The results showed significant effect of the wind direction on the flow patterns both inside and at the roof openings. Wind direction significantly affected the ventilation rate, airflow and crop temperature distributions. Measured ventilation rates are in reasonable agreement with estimated ventilation rates predicted by a model. However, air velocities at the greenhouse openings differed from the measured values.

Evaporative cooling is the most effective cooling method for controlling the temperature and humidity inside a greenhouse. However, its suitability is restricted to the respective region and climate as humid tropics seldom suits for its application due to high humidity levels [54]. By and large greenhouse users consider fan and pad systems or fan plus foggers as cooling systems [41].

Though various fan and pad systems are applied in greenhouses in many parts of the world today, the fan and fog system is also becoming popular among growers. There are well-defined standards on the greenhouse cooling systems based on fan and pad, and fan and fogging systems [56]. Parallel to the fan and pad systems is the cooling tower application for greenhouse air conditioning [57]. Large or leafy plants such as cucumber can themselves also serve as air coolers due to evapotranspiration from the leaf surfaces, provided that the plants are healthy and have proper irrigation. This type of cooling can be more effective if combined with shade and can decrease fan or ventilator capacity needs, eliminating the pad requirement [58,59].

An experiment was conducted by Kurklu and Bilgin [60] to cool a 15 m$^2$ ground area plastic-tunnel-type greenhouse by the use of a rock bed. Thermo-physical properties of the rock bed and air are presented in Table 3. Two rock-bed canals were dug in the soil, filled with the rocks and insulated; the top surface was covered by a soil layer of thickness enough for the root development depth of the plants. Air was pushed through the rock bed by a centrifugal fan with an 1100 m$^3$/h flow rate. Energy stored in the rock bed during the day was dumped outside the greenhouse at night using the cooler outside air. The results of the measurements showed that the rock-bed system maintained air temperature 14 °C lower at maximum in the experimental greenhouse than the control one. The temperature difference seemed to increase with increasing solar radiation and outside air temperature. Relative humidity during the day remained at about 40% in the experimental greenhouse and was always higher than that in the control one. The coefficient

of performance (COP) of the rock-bed system was higher than 3 in general, and it was observed that this value increased with decreasing rock-bed temperature. The average solar collection efficiency was 38%. The rock-bed system seems to have a significant potential for cooling applications in greenhouses.

Chandra et al. [61] had predicted the cooling pad temperature in a fan-pad cooling system in greenhouse. Under tropical condition of India, the most important environmental control requirement for greenhouses is cooling. The prediction of the temperature of the cooling pad area is important from the point of view of simulating the resultant microclimate under greenhouse since the cooling pad area become significant in relation to other surfaces exchanging heat in the greenhouse. Measurements of pad temperature have been made in an experimental greenhouse employing a fan pad cooling system. The results indicated the pad temperatures to be lower than the wet bulb temperatures of the surrounding ambient air.

Abdel-wahab [62] developed a mathematical model to estimate water evaporation rate, airflow rate and cooling effect in an evaporative cooling system for farm structures in Saudi Arabia. It was reported that covering the roof of the greenhouse with external shading would save an appreciable amount of energy and water consumption. Fuchs et al. [63] developed a procedure to evaluate the latent heat cooling by means of crop transpiration and free water evaporation from wet fan and pad system. They found that covering material property of 30% reduced solar radiation transmission at ventilation rate of 30 volume exchanges per hour maintained the temperature of greenhouse with in safe limits for growing rose crop during summer.

Cohen et al. [64] experimentally investigated the cooling efficiency of greenhouse by wetting the outer roof and inner crop soil surfaces where tomatoes were grown. They reported that wetting of roof had a smaller effect in reducing air and canopy temperatures than wetting the canopy. However, combination of both wetting treatments reduced inside air temperature by about 5 °C and canopy temperature by nearly 7 °C below the ambient condition. Willits and Preet [65] conducted an experiment with intermittent application of water over externally mounted shade net on greenhouse. The results revealed that rise of greenhouse air temperature were reduced by 41% under wet cloth as compared to 18% under dry cloth. Medina et al. [66] performed a study to evaluate the use of reflective aluminized polypropylene shading nets on photosynthetic performance of citrus plants and observed reduction in photo-synthetically active radiation (PAR) levels and leaf temperatures when the reflective nets were used. Shukla et al. [67] experimentally studied the effect of inner thermal curtain in the evaporative cooling. The results indicated that use of inner thermal curtain reduced the greenhouse temperature by 5 °C.

## 6. Experimental studies on crop cultivation

Soil temperature in glasshouses differing in orientation with and without tomato crops was measured by Whittle and Lawrence [68] for the period of five years. It was observed that the winter temperatures and the heat gain were consistently higher in an east–west house than in north–south house. This difference was related to a higher transmission of direct radiation by the east–west house. Again Whittle and Lawrence [69] measured air temperature in glasshouse differing in glazing and orientation for the period of five years. Horizontal and vertical gradients in unheated and unventilated houses were small or absent; in unheated house, gradients when they occurred were determined by the position and number of the heating pipes. It was observed that winter temperature were consistently higher in an unheated and unventilated east–west house than in a north–south house. The use of automatic roof ventilators reduced temperature fluctuation and in summer heat also reduced the mean excess temperature to 7–8 °F.

**Fig. 12.** Semi cylindrical greenhouse.

Yang et al. [70] used the point source and plant growth variable to characterise the microclimate of greenhouse cucumber crop. It was found that canopy heat temperature with high solar radiation was considerably lower than greenhouse air temperature due to high transpiration rate. The vertical component of air movement was a function of time with the maximum value occurring late at night due to air instability.

Off season cultivation of Poinsett variety of cucumber under plastic greenhouse was done by More et al. [71]. It achieve yield of 190.1 tonnes per hectare. Highest number of fruit (22.33) per plant with average weight of 337 g per fruit. UV stabilized plastic covered greenhouse was used for cultivation of vegetable crops by Nimje et al. [72] and compared its results with open field conditions. It was found that only okra and capsicum gave about three times higher yield was recorded inside the greenhouse as compared to that of open field conditions. The fruit yields of pepper in greenhouse were two and half times higher under greenhouse. The biomass yields were also higher by 5–6 times, selection of a proper variety of crop and time of planting was found to be a key to achieve maximum production in greenhouse.

An experiment on semi-cylindrical type greenhouse under composite climate at Udaipur (24°35′N, 73°42′E), was conducted by Kothari [73]. Three crops tomato, brinjal and isabgol were taken as experimental crops. It was reported that overall growth of the plant inside the greenhouse as compared to outside the greenhouse is better in terms of height and dry weight of the plant. Same greenhouse was used for raising *Albizia lebbeck* seedlings by Kothari and Panwar [74] and compared with open field conditions. Experimental results show that the height of the 3 months old seedlings of *A. lebbeck* was 135% more inside the greenhouse as compared to open field conditions. The corresponding increase in collar diameter in greenhouse was 50% and dry matter content was 215%. Similar study was conducted by Panwar et al. [7] on same type of greenhouse and location (see Fig. 12). The study was conducted with two medicinal crops viz. *Withania somnifera* and *Psoralea croylifolia* to evaluate cultivation performance and compare with field condition. The experimental results show that mean plant height of *W. somnifera* and *P. croylifolia* in greenhouse condition was 78.9 cm and 125 cm whereas it was 2802 cm and 50 cm in field condition respectively. The collar diameter for *W. somnifera* was 9.8 mm and 5.68 mm for greenhouse and field condition respectively. The collar diameter for *Psoralea corylifolia*, it was 10.8 mm in greenhouse and 5.96 mm for field condition was recorded. Total dry matter from *W. somnifera* and *P. croylifolia* inside the greenhouse was 92.9 g per

plant and 118.7 g per plant whereas it was 25.8 g per plant and 40.3 g per plant at field conditions.

Strawberry crop under greenhouse with the objectives of extension of growing season and to obtain good quality produce was cultivated by Sharma et al. [75]. It was concluded that strawberry could be successfully grown inside a greenhouse during winter season. The average yield per $m^2$ and per plant was found to 2.76 kg and 302 g respectively.

## 7. Conclusion

A comprehensive literature survey on thermal modeling, heating, cooling, ventilation, structural analysis and experimental study on crop production under greenhouse was made. The temperature difference increases inside greenhouse conditions with increasing solar radiation. Relative humidity inside greenhouse always observed higher than that of open filed conditions. East-west orientation is best suited for year round greenhouse applications at all latitudes as this orientation receives greater solar radiation. The average yield and dry matter in the greenhouse is observed higher that of open field conditions, early and higher germination rate also found good in greenhouse. It is also found that round year cultivation is quite possible by providing artificial microclimate for plant propagation which lead a renewable and sustainable farming practices specially for developing nations.

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